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Evaluating ecosystem processes in willow short rotation coppice bioenergy plantations

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Abstract

Despite a growing body of research linking bioenergy cultivation to changing patterns of biodiversity, there has been remarkably little interest in how bioenergy plantations affect key ecosystem processes underpinning important ecosystem services. In this study, we compare how the processes of predation by ground arthropods and litter decomposition varied between Short Rotation Coppice (SRC) willow bioenergy plantations and alternative land-uses: arable and set-aside (agricultural land taken out of production). We deployed litter bags to measure variation in decomposition, and a prey removal assay coupled with pitfall traps and direct searches to investigate variation in predation pressure. Decomposition rate was higher in willow SRC and set-aside than in cereal crops. Willow SRC had the highest abundance and diversity of ground-dwelling arthropod predators, but land-use had no detectable influence on predation of fly pupae or the combined activity-density of the two principal Coleoptera families (carabids and staphylinids). Overall, our study demonstrates that the conversion of arable land to SRC may have implications for the rate of some, but not all, ecosystem processes, and highlights the need for further research in this area.

Keywords: biodiversity, bioenergy, decomposition., ecosystem services, land management, predation, set-aside, willow SRC

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Introduction

The increased cultivation of biomass for biofuels (transport fuels) and bioenergy (heat and power) has provoked much debate about ecological consequences (Dauber *et al.*, 2010; Fargione *et al.*, 2010; Fletcher *et al.*, 2011). Many studies point to an inevitable loss of biodiversity, where the biofuel either replaces or threatens natural habitats (Danielsen *et al.*, 2009; Fayle *et al.*, 2010), or where the crop is an annual species such as maize or soybean (Meehan *et al.*, 2010; Fletcher *et al.*, 2011). In many parts of the northern hemisphere, however, a small, but growing proportion of biomass crops consist of tree species or perennial grasses planted into existing areas of intensively farmed arable land (Dauber *et al.*, 2010; Don *et al.*, 2012;). Often referred to as bioenergy crops (BECs) or second generation crops, their main uses are currently for the production of heat and power. As biofuel production technology develops, it is expected that they will also be used to produce liquid transport fuels (IEA Bioenergy, 2009; Rowe *et al.*, 2009).

Willow (*Salix* spp) short rotation coppice (SRC) is one of the most widely planted second generation bioenergy crop in Europe, with the area cultivated expected to increase greatly by 2050 (Rowe *et al.*, 2009; Don *et al.*, 2012). Interest in SRC cultivation is also accelerating in North America due in part to the potential these crops have to deliver a number of ecosystem services (Volk *et al.*, 2006; Tyndall *et al.*, 2011; Amichev *et al.*, 2012). Most research on the ecological impact of willow SRC has focused on studies of biodiversity (species richness, diversity and abundance) compared with local alternative land-use options (arable, grassland). For the most part, SRC seems to have neutral or even positive impacts on biodiversity (Dauber *et al.*, 2010; Fletcher *et al.*, 2011). For example, in comparison to arable land, both plant and arthropod communities become more species rich, with plant communities exhibiting an increased representation of perennial species (Cunningham *et al.*, 2004; Rowe *et al.*, 2011). Important changes to avian communities are also observed with a relative

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increase in species associated with scrub or woodland habitats (Sage *et al.*, 2006). It must be noted, however, that although overall diversity and species richness may be increased, some species such as birds associated with open farmland may decline in abundance (Sage *et al.*, 2006) and we have as yet only a limited understanding of the response of all species groups (Rowe *et al.*, 2009).

Changes in species composition resulting from a switch from arable crop cultivation to increased SRC cultivation may have wider repercussions on ecosystem processes and the provision of ecosystem services. The putative link between species composition and maintenance of ecosystem processes is widely debated as is the debate regarding whether species diversity or functional diversity is the main controlling factor in any relationship observed (Tilman *et al.*, 1997; Hooper *et al.*, 2005; Tylianakis & Romo, 2010) Understanding these relationship is, however, central to land management practice (Bengtsson *et al.*, 2000;) as well as wider ecological theory. For example, predator diversity may be important for herbivore pest control (Snyder *et al.*, 2006; Tylianakis & Romo, 2010), while a diverse pollinator assemblage also ensures a full pollination service to the plant community (Menz *et al.*, 2011). Information on the effects of management on ecosystem processes is consequently necessary to the development of predictive management models for major land-use change (Bengtsson *et al.*, 2000; Forup *et al.*, 2008).

Unfortunately, the long-standing emphasis on biodiversity patterns rather than ecological processes means that we have few data with which to accurately assess how a shift in land-use to BEC plantations might affect ecosystem service provision in agricultural landscapes (Werling *et al.*, 2011). In studies of restoration of degraded land, Forup *et al.* (2008) showed that ecological processes rather than just species richness and abundance provide a better comparison of restoration success. The relationship between biodiversity and ecosystem processes could be particularly important in willow SRC, where the pressure to maximize its yield and economic return (Moonen & Bàrberi, 2008) is balanced by interest in developing ecologically sympathetic management of SRC plantations for inclusion in agri-environment schemes (Valentine *et al.*, 2009). Linking biodiversity change to enhanced ecosystem service provision could provide a mechanism to better synergize commercial and environmental interests for likely future increases in SRC cultivation (Sage & Tucker, 1998).

SRC plantations are generally thought to be beneficial for various arthropod species, by virtue of their relative stability compared to arable systems, and their impact on plant community composition and structure (Sage *et al.*, 2006; Landis & Werling, 2010). It has been suggested that changes to the arthropod community in SRC plantations have concomitant effects on the ecosystem processes with which these organisms are involved (Gardiner *et al.*, 2010; Rowe *et al.*, 2011). The processes of decomposition and predation are, for example, tightly linked to arthropod species diversity and are vital for crop productivity and ecosystem stability via their respective influence on biogeochemical cycling and pest control (Hättenschwiler *et al.*, 2005; Ameixa & Kindlmann, 2008; Fountain *et al.*, 2009). A number of authors have highlighted the potentially vital role that arthropod predators play in the control of the many invertebrate herbivores found in poplar and willow SRC plantations (Sage & Tucker, 1998; Björkman *et al.*, 2004). Nonetheless, evidence is lacking to link the supposed benefits of SRC cultivation to ecosystem service provision. Here we describe a series of bioassay experiments designed to examined here how the key ecosystem processes of leaf decomposition and predation varied between SRC willow plantations and the most commonly encountered alternative land-use options: arable and set-aside

Materials and methods

Decomposition assay

Study sites. The study centred on three SRC willow plantations established on former arable fields between 1998 and 2000 in north Nottinghamshire, England. SRC plantations ranged in size from 5 to 9 ha and consisted of five willow varieties: 30% Tora, an equal proportion (20% each) drawn from three of Ulv, Olof, Jorunn or Jorr, and a small amount (10%) of Bowles Hybrid. Each of the three willow SRC plantations were independent plantations separated by minimum of 1 km. Arable and set-aside fields were selected for their proximity and similarity (size and shape) to the SRC plantations forming three sites (experimental blocks) each containing one willow SRC plantation, one arable field and one set-aside field..At the outset of our decomposition assay, set-aside was mandatory under the European Union Common Agricultural Policy (CAP). Given its perceived benefit for farmland biodiversity (Stoate *et al.*, 2009), it presented an obvious comparative land-use type. Cereal crops currently represent the highest fraction of arable land-use in Great Britain (Garthwaite *et al.*, 2011); consequently our final comparative land-use type was barley (*Hordeum vulgare* L.). Further site details and selection criteria of the nine fields used (i.e. three SRC, three set-aside, three barley) can be found in Rowe *et al.* (2011).

Experimental treatments. A comparison of decomposition rates in the three land-use types was performed using 170 mm × 180 mm litter bags. Half of the bags incorporated 5 mm nylon mesh (White Boots body polishing sponge, Boots PLC, Nottingham, England), allowing access by most soil fauna including earthworms (Šlapokas & Granhall, 1991).

The remaining bags were made from 1 mm nylon mesh (Fabric world, Southampton, England) to restrict access by soil macrofauna and thus assay the relative importance of soil macrofauna and microbial/mesofauna (Šlapokas & Granhall, 1991). As species-specific variation in litter quality can influence decomposition rate (Kazakou *et al*., 2009), all bags were filled with nettle (*Urtica dioica* L.) leaves on the basis that the species was present at all field sites (Rowe *et al*., 2011). To ensure consistent leaf quality, fresh leaves were collected from a single population in Southampton (50°5609″N, 1°24′11″W) by removing them from the main stem and rejecting damaged or senescing leaves. The leaves were wilted overnight at room temperature to reduced sting cell activity before being cut into 2 cm^2 segments to standardize leaf size. Leaf fragments were dried at 60 °C for 24 h to reduce water content. Each litter bag was filled with 2 g of dried leaf material and then sewn closed.

A pair of litter bags of each mesh size was pinned 1 m apart on the soil surface at each of 10 locations in every field. Five bag pairs were located in the cultivated area of each field; one pair at the apex of four transect lines running at 90° from the field centre and four others located along each transect line at a distance 35 m from the crop edge. A further five bag pairs were located in the field margins (headlands). One pair on each transect and one additional pair in one randomly selected corner of the field. The litter bags were installed in mid July 2007 immediately following barley harvest, and they were left *in situ* for four weeks. Extreme care was taken when removing the bags from the field to avoid any litter loss on removal. In addition, little bags were placed inside individual paper bags to prevent litter loss during transport to and from the field site. Upon recovery and opening, any remaining nettle leaf material was separated from other extraneous plant material before being dried at 60 °C for 24 h. The fraction of total litter biomass loss per bag was quantified and arcsine square root transformed prior to analysis of mean biomass loss per field.

All bags in the cultivated area of one of the set-aside fields were lost when the landowner rotivated the field, and a further eight bags could not be relocated from the remaining fields. These losses precluded analysis by split-plot design; instead we used an unbalanced three-way ANOVA with Type III adjusted mean squares to examine the effect of mesh size, location (headland or cultivated area) and land-use on mean biomass loss.

Predation

Study sites. The predation assay was conducted in the same three SRC willow plantations described above. By the start of the predation experiment (2008), the EU had abandoned its policy of set-aside provision and all fields given over to set-aside in our study area had been returned to arable production. Consequently, we compared predation rates in willow SRC with the major alternative land-use option, which was cereals. Our predation assay was performed on three separate occasions during 2008, in spring (March/April), summer (June/July) and autumn (Sept/Oct). Two of the cereal fields used contained winter wheat with the remaining field containing barely; crop cover changed during this period to reflect the natural cropping cycle (Table 1). In addition, one of the three willow SRC plantations was harvested during autumn 2007; thus ground cover and crop height were greatly reduced. Again, this harvest is part of the normal management for this crop and probably had a minimal effect on ground-dwelling arthropod assemblages (Sage & Tucker, 1998).

Experimental treatments–assay experiment. Coleoptera are one of the most important ground-dwelling arthropod predators in the agri-environment (Lang, 2000; Ameixa & Kindlmann, 2008) and are also abundant in willow SRC plantations (Sage & Tucker, 1998). The predation assay therefore focused on this group, although assessments were also undertaken of the abundance and diversity of other ground-dwelling, predatory arthropods.

Predation pressure was measured with a prey removal assay, using *Drosophila melanogaster* Meigen pupae in an exclosure that limited access by birds and small mammals. Diptera pupae are a common standard for predation studies with Coleoptera and removal rate has been shown to correlate well with predator abundance (Speight & Lawton, 1976; Lys, 1995). In comparison to larvae or imagos, pupae are immobile, relatively long-lived and decay slowly once dead. Laboratory-reared *Drosophila* pupae were collected after pupation of approximately 90% of the culture. Prior to use, all dead or newly metamorphosed pupae were removed and the remainder killed by freezing at −20 °C to prevent imago emergence during the experiment; freezing in this way does not affect predation rates (Speight & Lawton, 1976).

Drosophila pupae were presented in the field under white ceramic tiles (150 × 150 × 5 mm; Homebase Ltd, Stafford, UK), supported 8 mm above-ground by two wooden blocks (8 mm × 40 mm × 8 mm) glued to opposite edges of the tiles to prevent access by small mammals and birds (Speight & Lawton, 1976; Lys, 1995). Five pupae were placed under each tile on a 50 mm^2 brown felt mat to aid recovery (Menalled *et al*., 1999). Nine tiles were positioned within the cultivated area of each field, one at the junction of four transect lines running at 90° from the field centre, and two on each transect, at a distance 25 and 50 m into the crop from its outer edge. This design maximized the spread of sample points across the field while aiming to limit impact upon the crop (Rowe *et al*., 2011). Pupae were placed under the tiles at dusk (within 3 h of sunset) and again at dawn (within 3 h of sunrise), when the number of missing pupae were noted and then replaced. This process was repeated for 3 days and the experiment was repeated three times, during March, August and November 2008.

Pupae removal rates for each field were determined for each season by calculating the hourly rate of pupae removal for the periods of dawn to dusk (daytime) and dusk to dawn (nighttime). Hourly removal rate was used to correct for seasonal variation in day length. Following arcsine transformation, these data were input as responses in a nested split-plot ANOVA with fixed factors of 'Season' (spring, summer and autumn), 'Time' (day and night) and 'Land-use' (willow SRC and cereal crop). The random factors of 'Field' nested in 'Block' accounted for the single field of each land-use type in each of three sites. The ANOVA model is:

Table 1 Details of field sites used to compare how two key ecosystem processes (decomposition and predation by ground-dwelling arthropods) varied between short-rotation coppice bioenergy plantations and adjacent arable cropping systems

Land-use	Site	OS Grid ref	Size (ha)	Established/ Drilled	Date of Harvest	Crop Characteristics		
						Spring	Summer	Autumn
Willow SRC	1	SK667 848	7.67	2000	2005	Mature crop 3–4 m, with extensive cover of ground flora, >80%	Mature crop 3. 2–5.8 m, with extensive cover of ground flora, >80%	Mature crop 4–6.6 m, with extensive cover of ground flora 50%–80%
Willow SRC	2	SK790 936	9.00	1998	2007	Cut back stools yet to reshoot, low ground flora 0.05–0.40 m providing patchy 30%–90% ground cover	Maturing crop 1–2 m, canopy closure near complete with extensive ground flora 80%–100% cover	Maturing crop 2–4 m, with extensive ground cover flora, but a few bare patches 10%–90%
Willow SRC	3	SK805 944	5.75	1998	2004	Mature crop 3–4.5 m, with extensive ground flora 90%–100% cover	Mature crop 3–5.5 m, with extensive ground 90%–100% cover	Mature crop 4–6 m, with extensive ground 80%–100% cover
Arable (Winter barely)	1	SK670 836	11.56	Oct 07	Aug 08	Low growth 0.06–0.10 m, of barely seedlings providing 50%–80% ground cover	Mature crop 0.60–0.70 m, providing 70%–90% ground cover	Stubble with weeds, 4–30 cm providing 40%–60% ground cover.
Arable (Winter wheat)	2	SK800 936	5.32	Oct 07	Aug 08	Low growth of wheat seedlings 0.10–0.27 m providing 30%–65% ground cover.	Mature crop 0.60–0.70 m, providing 60%–90% ground cover	Bare ploughed field
Arable (Winter wheat)	3	SK 809 944	5.80	Oct 07	Aug 08	Low growth of young seedlings 0.07–0.20 m providing 25%–45% ground cover	Mature crop 0.60–0.80 m, providing 60%–90% ground cover	Stubble with weeds, 0.09–0.60 m providing 25%–70% ground cover.

Height measurements give maximum and minimum values taken on three randomly selected plants at each of the nine sampling locations in the crop utilized within the predation assay; cover values give maximum and minimum visual estimates of percentage of ground cover to the nearest 10% over 4 m^2 at each location. In the willow sites, additional canopy cover was present and, unless otherwise stated, canopy closure had been achieved in all sites

$$Y = S_3|T_2|Fi'_1(B'_3|L_2) \qquad \textit{Model 1}$$

Model 1 where subscripts show the number of factor levels, '|' signifies 'cross-factored with' and '(' signifies 'nested in' (following the nomenclature of Doncaster & Davey, 2007).

Experimental treatments–Arthropod activity and abundance. Predation rates have been closely related to pitfall trap catches (Menalled *et al.*, 1999). Pitfall catches were therefore used to compare the likely predation impact of Coleoptera between different land-uses. Pitfall traps cannot separate the independent impacts of behavioural activity and population density (Menalled *et al.*, 1999; Lang, 2000; Thomas *et al.*, 2006), and the activity of at least one predatory beetle family (the Carbidae) is influenced by vegetation cover (Thomas *et al.*, 2006), a factor that varies greatly between SRC and adjacent land-use types (Rowe *et al.*, 2011). We distinguished between changes in density and activity by searching directly for beetles to measure predator abundance independently of their activity as estimated from the combined search and pitfall trap data.

Pitfall Traps. One 80 mm diameter pitfall trap filled to 60 mm with a 1% detergent solution was installed 5 m away on an axis parallel to the field margin tiles. The separation of 5 m provides a realistic measure of beetle activity-density without affecting visits to the pupae (Ward *et al.*, 2001). Trapped arthropods were collected at dawn and dusk alongside exclosure checks and stored for later identification. To correct for seasonal variation in day length, the number of individuals caught in pitfall traps was converted to an hourly rate of individuals trapped from dawn to dusk (daytime) and dusk to dawn (night-time).

Direct Searches. We undertook hand searches using a metal frame (300 mm × 300 mm × 300 mm) forced into the soil surface 5 m away from each tile. Surface vegetation inside the frame was visually searched for predatory arthropods (which were retained) before all soil to a depth of 50 mm was removed, bagged and chilled (4 °C) for later analysis. Soil was then hand sorted in laboratory and all predatory invertebrates retained, together with all Coleoptera and Hemiptera (excluding aphids) as their identification to family-level could only be confirmed on preserved specimens with magnification.

Table 2 Comparison of leaf decomposition rates between land-use types of willow short rotation coppice, arable fields and set-aside fields. Mean biomass loss of *Urtica dioica* leaves in relation to land-use type, field location (headland vs. cultivated area) and litter bag mesh size (1 or 5 mm) was compared using three-way ANOVA with type III adjusted MS. $P < 0.05$ denoted in bold type

Factor	DF	MS	*F*	*P*
Land-use	2	281.08	4.40	0.025
Location	1	12.91	0.20	0.657
Mesh size	1	391.77	6.13	0.021
Land-use × Location	2	13.11	0.21	0.816
Land-use × Mesh size	2	60.68	0.95	0.402
Location × Mesh size	1	60.95	0.95	0.339
Land-use × Location × Mesh size	2	13.06	0.20	0.817
Residual Error	22	63.81		

The direct searches provided a measure of ground-dwelling predatory arthropod abundance. Activity was then defined as the relative number of captures per individual, given by dividing the number of individuals per search into the number of individuals per pitfall trap.

Coleoptera abundance data were square root transformed, and input as responses in a split-plot nested ANOVA with fixed factors of 'Family' (Carabids and Staphylinids), 'Season' (spring, summer and autumn) and Land-use (willow SRC and cereal crops). The random factors of 'Field' nested in 'Block' accounted for the single field of each land-use type in each of three sites. The model used is:

$$Y = F_2|S_3|Fi'_1(B'_3|L_2) \qquad \textit{Model 2}$$

Activity-density of the most abundant Coleoptera families for each field was determined for each season. Following square root transformation, these data were input as responses in a nested split-plot of the above design augmented by an extra fixed cross-factor of 'Time' (day and night). The ANOVA model is:

$$Y = F_2|S_3|T_2|Fi'_1(B'_3|L_2) \qquad \textit{Model 3}$$

In all split-plot models, *post hoc* testing of significant effects amongst three-level factors was performed using orthogonal contrasts with family-wise adjustment of α (Doncaster & Davey, 2007).

Results

Decomposition assay

Urtica leaf biomass loss varied greatly according to land-use type (Table 2); post hoc *S-N-K* tests revealed that leaf decomposition in the cereal crops was much reduced in comparison with that recorded in set-aside or willow SRC (Fig 1). Decomposition was not influenced by the location of litter bags in field headlands or cultivated areas, but did vary according to mesh size, with consistently more biomass loss in the 5 mm mesh bags (Table 2).

Predation assay

Overall, 2.2% ± 0.31% and 2.4% ± 0.30% of the available Drosophila pupae were removed per hour in the willow SRC and cereal crops respectively (total over the total time period 29% of all the pupae provided). Predation rate did not vary with Land-Use (cereal vs. SRC) or Time (day vs. night); it did depend on Season ($F_{2,20} = 28.84$, $P = 0.001$), increasing by over twofold in

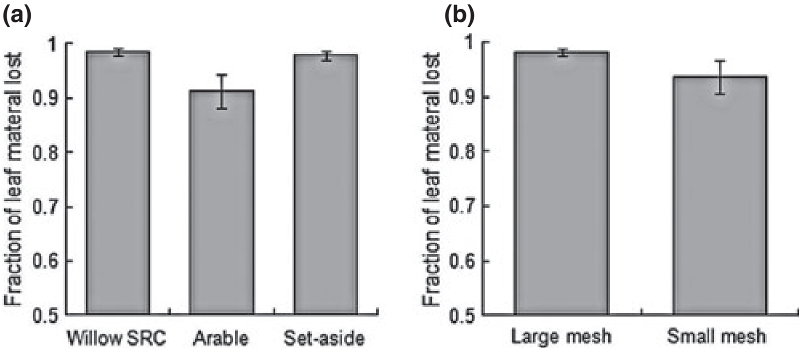

Fig. 1 Mean ± SE fractional loss of biomass for *Urtica dioica* leaves held in 1 and 5 mm litter bags for 4 weeks. (a) Variation between willow short rotation coppice plantations, arable (recently harvested barley) and set-aside fields; lower-case letters above bars identify the significant difference between treatment means in a post hoc *S-N-K* test at $P < 0.05$ following three-way ANOVA. (b) Variation by mesh size ($P < 0.05$).

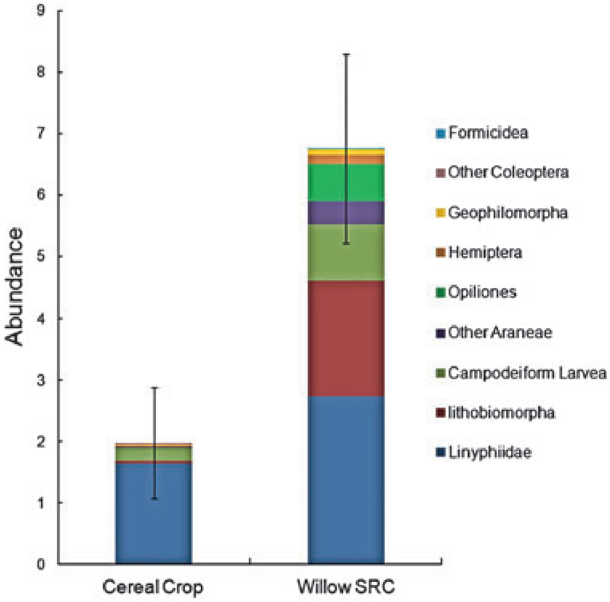

Fig. 2 Mean ± SE abundance of predatory arthropods (not including Carabid and Staphylinid beetles, see Fig 3) recovered from soil samples (0.3 m × 0.3 m × 0.05 m) taken from cereal and willow short rotation coppice crops. Bars are divided to show relative abundance of families or grouped families in the case of rarer families.

summer, without interactions with any other treatment factors (ANOVA table in S1).

Arthropod abundance and activity

Beetles were by far the most common predatory arthropods encountered in pitfall trap and hand search samples (59% of all predatory arthropods), with the majority of species belonging to the Staphylinidae and Carabidae. The next most common arthropods were spiders (25%) and Chilopoda (6%). Although none of these other predatory families was present in sufficient numbers for individual statistical analysis, we found that the overall abundance of noncoleoptera estimated from hand-sorted soil samples of predatory arthropods was more than three times higher in willow SRC than in cereal crops (Fig. 2, $F_{1,2} = 20.41$ $P = 0.046$, full ANOVA table in S2).

To allow comparison with the predation assay, Staphylinids and Carabids were analysed together for their activity-density, abundance and activity, because these are the most likely predators of fly pupae (Lewis, 1964; Lys, 1995; Menalled *et al.*, 1999). The addition of 'Family' as a treatment factor nevertheless allowed for possible differences in the response of Staphylinids and Carabids to land-use or other treatments (identified from significant interactions with Family). The pitfall catches, estimating combined activity-density of Staphylinids and Carabids, were similar across the land-uses ($F_{1,\,2} = 2.68$ $P = 0.243$), as was activity and abundance (see S3 for full ANOVA table). Staphylinid abundance however, was higher in willow SRC compared to cereals, while Carabid abundance was unaffected by crop type (Fig. 3a, Family × Land-use $F_{1,20} = 5.51$ $P = 0.029$). The activity of the beetle families also varied with land-use (Family × Land-use $F_{1,44} = 6.14$ $P = 0.017$), with Carabids being more active in cereals than willow SRC (Fig. 3b). The increased abundance of Staphylinids, and lower activity of Carabids in willow SRC was also reflected within the pitfall catches (Fig. 3c, Family × Land-use $F_{1,44} = 9.30$ $P = 0.004$).

Although the absence of main effect of land-use in the pitfall trap data is consistent with the results of the pupae removal assay, test for a correlation between the two factors showed no detectable relationship ($F_{1,8} = 0.18$, $P = 0.686$, tested by adding the pitfall data as a predictor variable in model 1).

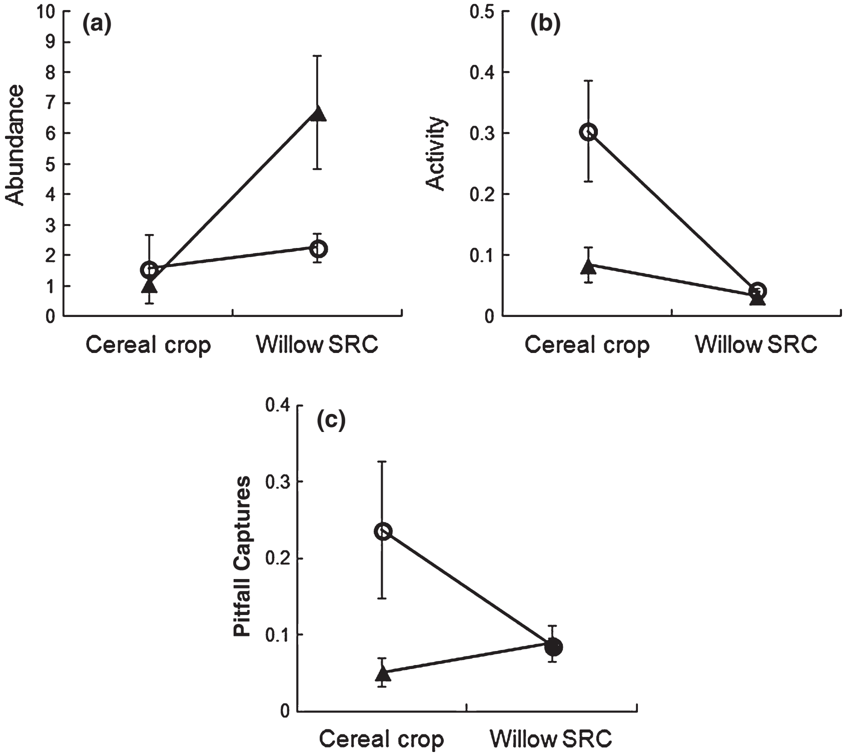

Fig. 3 (a) Mean ± SE abundance of Staphylinids (triangles) and Carabids (open circles), given by mean number of individuals per 0.3 m × 0.3 m × 0.05 m soil sample; (b) activity given by mean number of individuals per hour per pitfall/mean number of individuals per soil sample; and (c) pitfall captures given by mean number of individuals trapped per hour per pitfall trap.

Spatio-temporal variation

Coleoptera activity-density was lowest in the spring, rising in the summer and autumn ($F_{2,44} = 19.02$, $P = 0.001$, detailed in S3), with mean captures per hour of 0.02 ± 0.009 in spring, 0.18 ± 0.052 in summer and 0.142 ± 0.01 in autumn. In both cereal crops and willow SRC, the increase in activity-density followed increases in abundance from a mean number of individuals per unit area of soil sample of 0.45 ± 0.11 in spring to 3.15 ± 0.87 in summer and 5.10 ± 0.76 in autumn ($F_{2,20} = 22.23$, $P = 0.001$). The number of individuals trapped in pitfalls also varied with time of day ($F_{1,44} = 5.24$, $P = 0.027$). More beetles were captured during the night than during the day (respectively, 0.15 ± 0.01 and 0.08 ± 0.02 individuals trap^{-1} h^{-1}).

Discussion

In the USA alone, the annual economic value of arthropod-mediated ecosystem services for crop production has been estimated at $13 billion (Losey & Vaughan, 2006). Clearly therefore, any contribution that BECs can make to maintaining or increasing invertebrate biodiversity in the agri-environment is an additional environmental benefit to any contribution to reductions in global CO_2 emissions. A number of studies have demonstrated a relatively positive role of BEC plantations for arthropod biodiversity; effects are most often associated with the increased habitat stability and floral diversity compared to arable fields (Gardiner *et al.*, 2010; Rowe *et al.*, 2011). To date, however, few authors have gone beyond speculation that changes in biodiversity patterns have any impact on ecosystem processes (Werling *et al.*, 2011). In this study, we explicitly examine how BEC cultivation affects two aspects of ecosystem service provision. We show that decomposition rates in SRC plantations increased in comparison with conventionally farmed arable crops, but that predation rates by ground-dwelling beetles were broadly comparable between SRC and arable.

We found higher litter loss in willow SRC and set-aside than in cereals. Previous studies have shown that soil faunal abundance and microbial activity can be reduced by the tillage, pesticide use and lower biomass input associated with arable cropping systems when compared with set-aside (Curry *et al.*, 2002; Minor & Cianciolo, 2007). Makeschin (1994) also reports that willow SRC plantations support higher numbers of earthworms and woodlice than arable systems and that

SRC plantations generally have higher microbial biomass and soil faunal diversity than arable soils. Consequently, although not quantified here, it is likely that increased decomposition within willow SRC was associated with a higher abundance and/or activity of the soil decomposer community. Any increase in the abundance or activity of the soil decomposer organisms in SRC could have important benefits for ecosystem function and service provision. Soil structure and stability are closely linked to decomposer activity, particularly earthworms (Lavelle *et al.*, 2006). An abundant and diverse soil fauna also represents an invaluable food source for above-ground predators such as beetles and Linyphiid spiders (Birkhofer *et al.*, 2008; Hartwood *et al.*,2009), the two most common predatory arthropods found in this study. Higher soil fauna activity could therefore aid in provision of a number of ecosystem services.

Although a number of previous studies (Speight & Lawton, 1976; Lys, 1995; Menalled *et al.*, 1999) report a positive correlation between catches in pitfall trap and removal of prey items, like Fountain *et al.*, 2009; Ameixa & Kindlmann, 2008; we found no such relationship. Direct comparison between studies is difficult due to different methodologies; however, predation rates in our study appear to be lower than that reported by Speight & Lawton (1976) where 25 *Drosophila* pupae presented in a single location were removed in 24 h. Predation rates were also higher in the study by Lys (1995) where 58% of the pupae presented were attacked (in this case, individual pupa were presented at 64 different sampling points and checked on an hourly basis)

Our analyses of prey removal and predatory beetle activity-density also failed to detect a main effect of land-use, most likely reflecting the contrast between high abundance of Staphylinids in willow SRC and high activity of Carabids in cereal crops. Increases in Staphylinid abundance and diversity have been reported, respectively, in orchards (Balog *et al.*, 2009) and fallow land (Dauber *et al.*, 2005) compared to arable. These observations are generally linked to the reduced light levels, favourable microclimate and more diverse food resources provided by increased ground flora in the former habitats (Dauber *et al.*, 2005; Balog *et al.*, 2009). These characteristics are shared by Willow SRC which often supports high weed cover and invertebrate diversity (Rowe *et al.*, 2009, 2011).

While Staphylinidae were more abundant in SRC compared to arable, Carabidae were more active in arable vs. SRC. The net result of the differences in abundance and activity of these two beetle families was that predation rates did not differ between habitats. Carabid activity is influenced by a number of factors including humidity, vegetation complexity and hunger (Lovei & Sunderland, 1996; Thomas *et al.*, 2006). Carabidae may have found it easier to move through the less complex ground cover within the arable field. Hunger may also have been an influence, as the similar levels of predation between the land-uses suggest that the higher activity levels were associated with consumption of the prey items. The structural diversity and composition of the willow SRC crop may have increased the abundance of potential food items for predators (Sage & Tucker, 1998; Sage, 2008). In addition, the pupae of leaf beetles (*Latin binomial*), one of the main pest species in willow SRC, are found at the soil surface in willow SRC and are highly acceptable to the ground beetle *Pterositichus niger* (Sage & Tucker, 1998).

Although predation rates did not vary detectably between SRC and cereal crops, we found over three times more arthropod predators in SRC. The SRC arthropod community was also more diverse including taxa such as harvestmen (Opiliones), a large number of Lithobiomophid centipedes and many other spiders ('Other Arenae') not captured in cereals. Experiments using alternative types of prey items not favoured by predatory beetles might reveal differences in predation rates between habitats. Thus, despite the lack of any obvious land-use effect within this study, the increased predator diversity in willow SRC may yet have a positive role in pest control, although this would depend on whether, predatory species have complementary functional roles (Snyder *et al.*, 2006; Tylianakis & Romo, 2010). There may also be positive effects on pest control within the wider landscape. In a recent study in the US, Werling *et al.*, 2011 reported a positive link between perennial bioenergy grass cultivation and landscape-scale predation of the eggs of corn-ear worms (*Heliothis zea*). The authors suggest that this was due to the high predator abundance in the bioenergy crops acting as a source of predatory species for the adjacent agricultural crops (Werling *et al.*, 2011). It is possible that willow SRC could provide a similar source of predators within the agri-environment, and certainly the potential for predator spill-over from SRC crops into adjacent arable crops seems worthy of further attention.

We show that SRC willow plantations can benefit certain aspects of biodiversity in the agri-environment, and for decomposition at least, our results suggest that at least one key ecosystem service could be enhanced by SRC cultivation. These findings support the notion that willow SRC crops may benefit the environment compared to intensive arable land-use systems (Sage & Tucker, 1998; Sage *et al.*, 2006; Valentine *et al.*, 2009), and they add weight to the argument that willow SRC should be considered for inclusion within Agri Environment Schemes (Sage *et al.*, 2006; Valentine *et al.*, 2009). Indeed, the strategic planning and planting of second generation bioenergy crops across the arable landscape could be used to bolster biodiversity and enhance ecosystem service provision in and around bioenergy plantations, with potential benefits to neighbouring crop yields. To test the validity of these ideas, further research needs to focus not only on the immediate biodiversity in and around BEC plantations but also on determining whether increased biodiversity delivers enhanced ecosystem service provision at the crop and landscape scale.

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Supporting Information

Additional Supporting Information may be found in the online varsion of this article:

Table S1. Split plot ANOVA on *Drosophila* pupae removal rates per hour by predatory arthropods in willow short rotation coppice plantations and cereal crops.
Table S2. Split plot ANOVA comparing abundance of non-coleopteran predatory invertebrates in willow short rotation coppice and cereal crops. Staphylinid and carabid beetles were analysed separately.
Table S3. Split plot ANOVA comparing pitfall catches, abundance and activity of Coleoptera in the willow short rotation coppice and the cereal crops (main-text ANOVA models 2 and model 3).